

# HOM Beam Based Diagnostics at FAST

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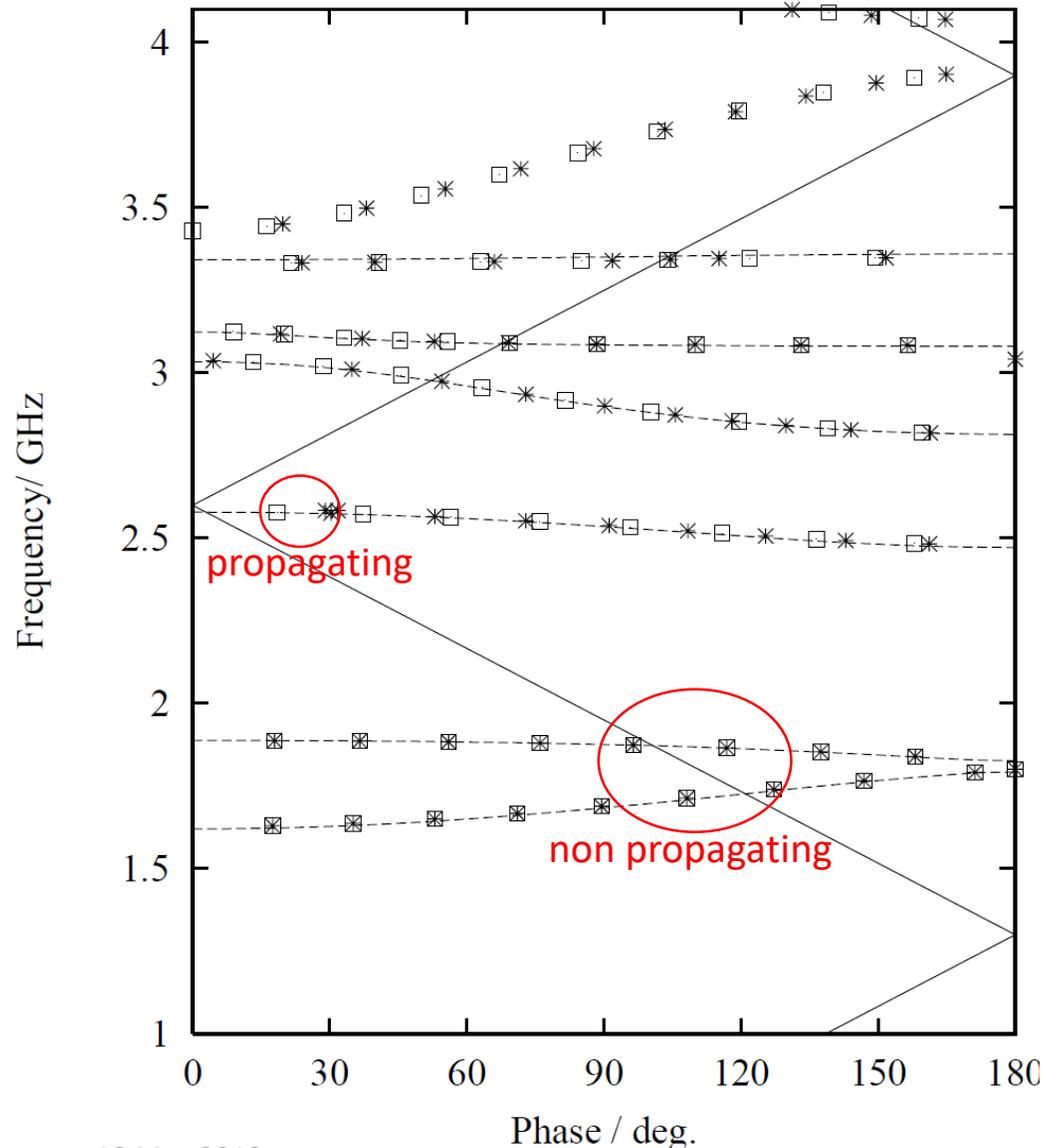
# Introduction

*Superconducting RF cavities are high quality symmetric resonators that support many different modes of oscillation, with high precision signals and unsurpassable dynamic range. Owing to their approximate axial symmetry, modes can be identified according to their monopole, dipole and quadrupole nature. Higher Order Modes (HOM) excited by bunched beams in SRF cavities hence coupled respectively to the charge, position and size of the beam.*

*HOM-based diagnostics have already been used in various SRF accelerators like FLASH at DESY and FAST at Fermilab. However, the complete exploitation of their full potential in beam diagnostics and beam based tuning has not been realized, for instance in achieving minimal transverse wake kicks and transverse beam size measurement, in a non-invasive fashion.*

*We would like to explore and identify physics and engineering challenges in implementing HOM diagnostics using fully relativistic electron bunches through CM2 SRF cavities at FAST.*

# TESLA Cavity Dipole Mode Passbands (axial symmetry)



mode	$f$ /GHz	$(R/Q)^{(1)}$ / $\Omega/\text{cm}^2$
Band 1		
MM- 1	1.6291	2x 0.0014
MM- 2	1.6369	2x 0.0636
MM- 3	1.6497	2x 0.0015
MM- 4	1.6671	2x 0.3767
MM- 5	1.6885	2x 0.0684
<b>Band 1</b>	<b>MM- 6</b>	<b>2x 5.5335</b>
	<b>MM- 7</b>	<b>2x 7.7852</b>
	MM- 8	2x 1.0492
	MM- 9	2x 0.8045
	MM-10	2x 0.3542
Band 2		
	MM-11	2x 0.2433
	MM-12	2x 0.1327
<b>Band 2</b>	<b>MM-13</b>	<b>2x 3.1825</b>
	<b>MM-14</b>	<b>2x 4.4887</b>
	MM-15	2x 1.0501
Ref. R. Wanzenberg (DESY)	MM-16	2x 0.0210
	MM-17	2x 0.0808
	MM-18	2x 0.0015
<b>Band 3</b>	<b>MM-30</b>	<b>2x13.1601</b>

# TM-like Dipole Mode ( $m=1$ ) Impedances

$$E_z(\theta) = E_z^{(0)} \cos(\theta - \theta_0)$$

On the polarisation plane:

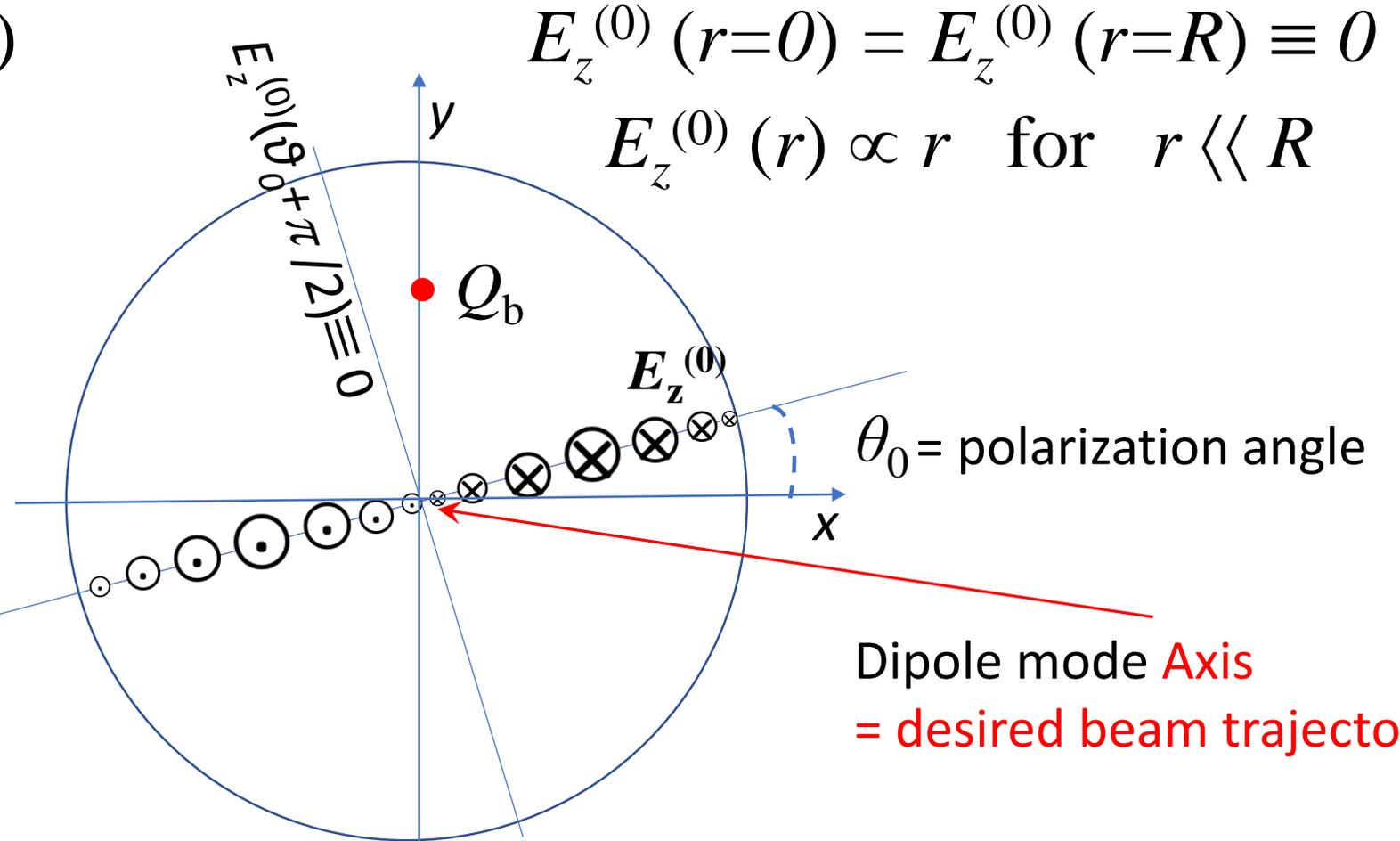
$$U = \int dz E_z(z, t=z/c)$$

$$\propto rU'$$

$$R/Q^{(m=1)} = U'^2 / \omega_{RF} W$$

Off the polarisation plane:

$$U(\theta) = U \cos(\theta - \theta_0)$$

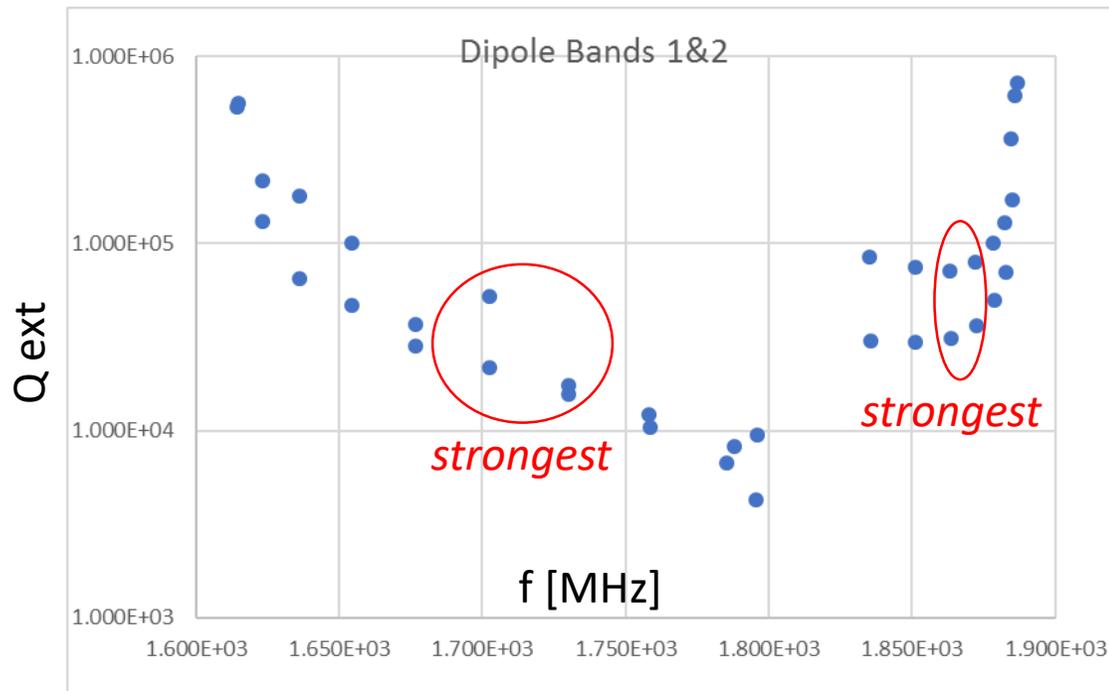


For axially symmetric RF structures, the choice of orthogonal polarization planes is arbitrary, and all modes electric axis coincide with the geometric axis.

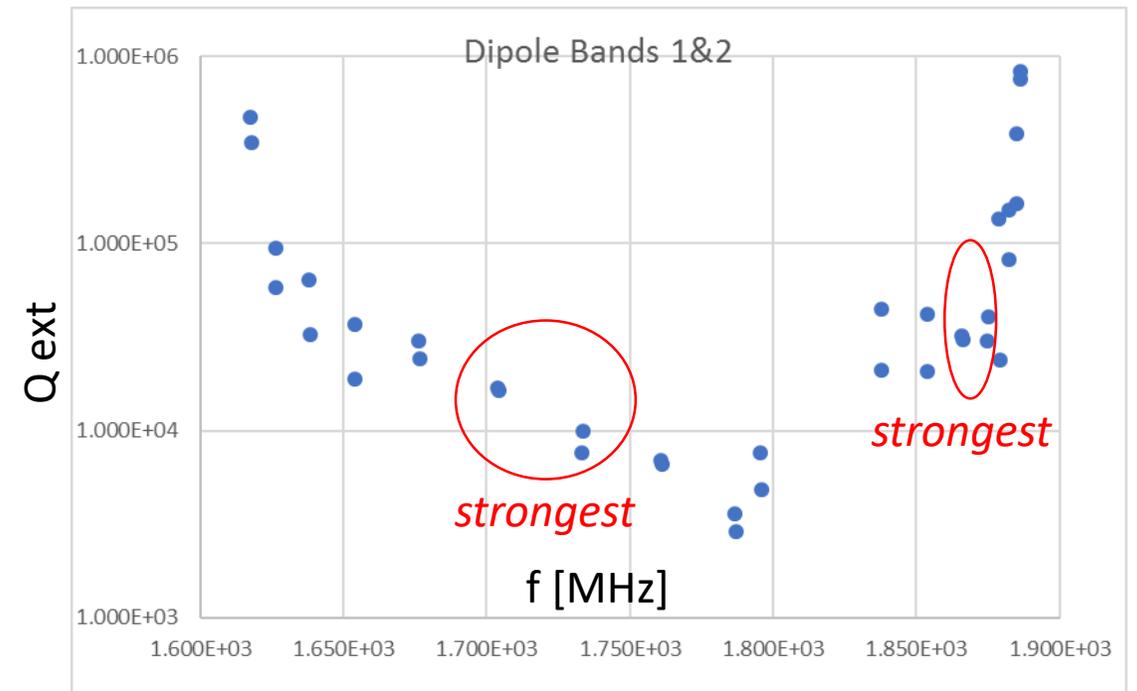
# Dipole Mode 1<sup>st</sup> and 2<sup>nd</sup> Passbands

- The fabrication errors and coupler ports are ‘weakly’ breaking the axial symmetry, hence lifting the mode degeneracy.
- Note the arrangement in polarization doublets (CM2 data also available)

CC1 dipole: 1<sup>st</sup> and 2<sup>nd</sup> passbands



CC2 dipole: 1<sup>st</sup> and 2<sup>nd</sup> passbands



# Dipole Mode ( $m=1$ ) Excitation Amplitudes

Assuming that both polarisations have the same center and beam coupling factor, for  $r \ll R$  :

$$A_1(Q_b) = C \langle r \cos(\theta - \theta_0) \rangle = C \langle u \rangle$$

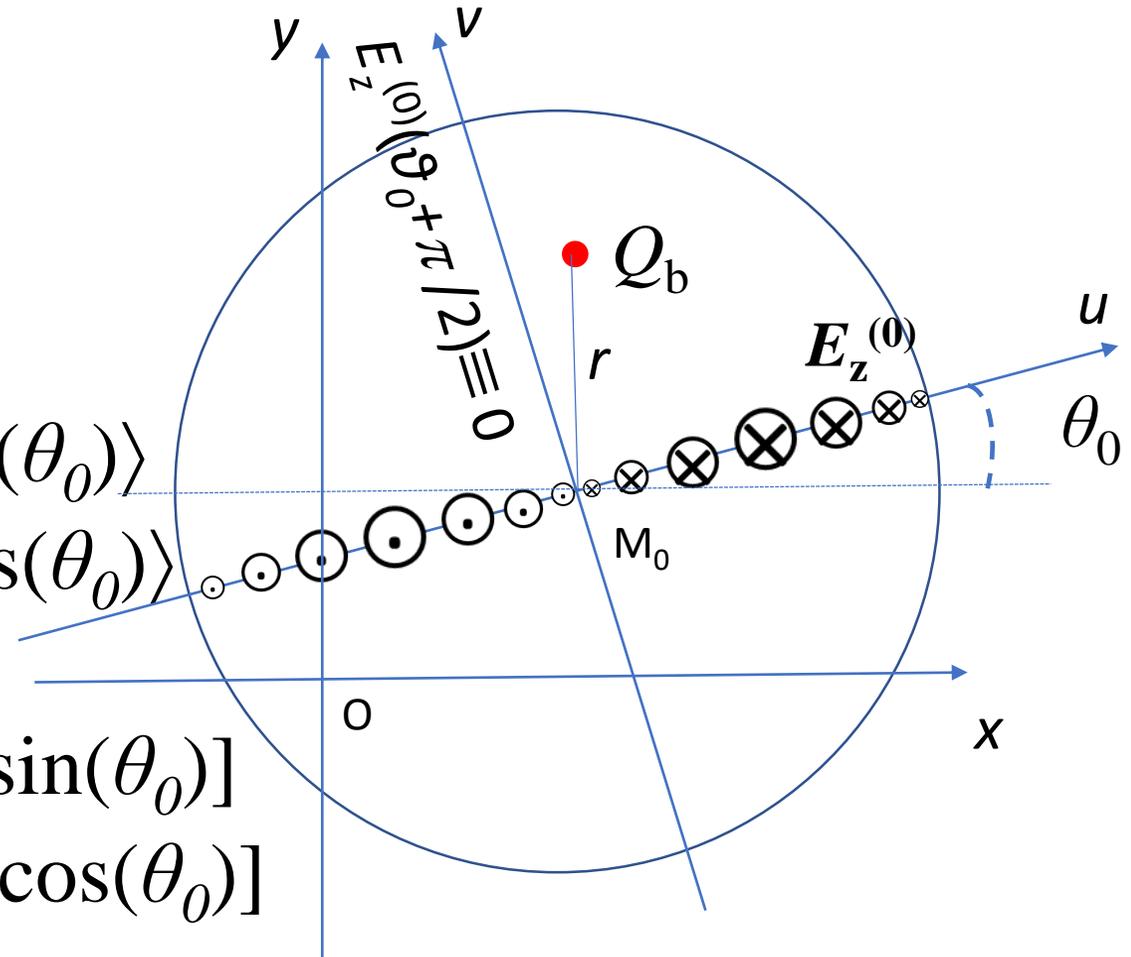
$$A_2(Q_b) = C \langle r \sin(\theta - \theta_0) \rangle = C \langle v \rangle$$

$$A_1(Q_b) = C \langle (x - x_0) \cos(\theta_0) + (y - y_0) \sin(\theta_0) \rangle$$

$$A_2(Q_b) = C \langle -(x - x_0) \sin(\theta_0) + (y - y_0) \cos(\theta_0) \rangle$$

$$A_1(Q_b) = C [(\langle x \rangle - x_0) \cos(\theta_0) + (\langle y \rangle - y_0) \sin(\theta_0)]$$

$$A_2(Q_b) = C [-(\langle x \rangle - x_0) \sin(\theta_0) + (\langle y \rangle - y_0) \cos(\theta_0)]$$



# Measurement plans

- Measure the two polarizations for each major dipole mode, usually separated by 1 MHz or less.
- Determine the horizontally / vertically most coupled modes.
- Single bunch data 1 nC is enough

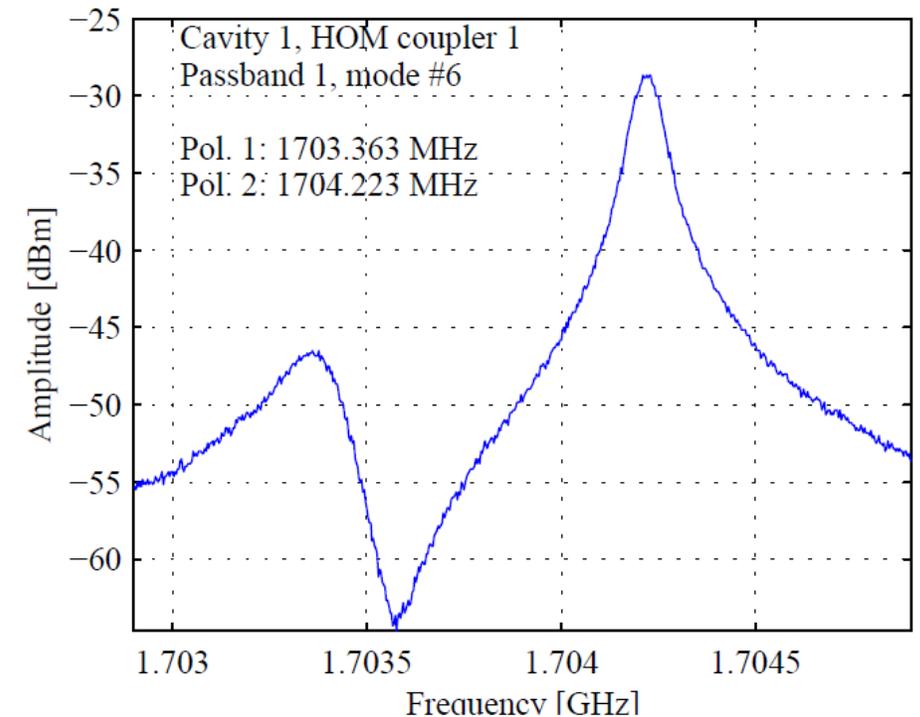


Figure 2: Mode #6 of the first dipole passband in cavity 1 of ACC1

Example of a FLASH cavity

# Measurement electric center

- Steer the beam through the HOM center by minimizing signals

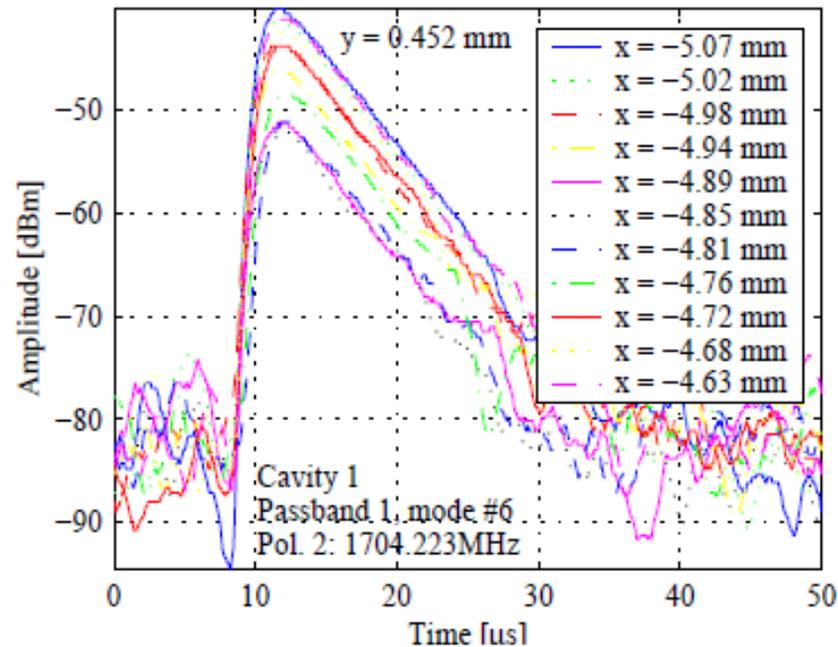


Figure 4: Time domain signals for the first polarization of the 6<sup>th</sup> mode of the 1<sup>st</sup> dipole band of the first cavity.

Example of a FLASH cavity: 50 μm steps

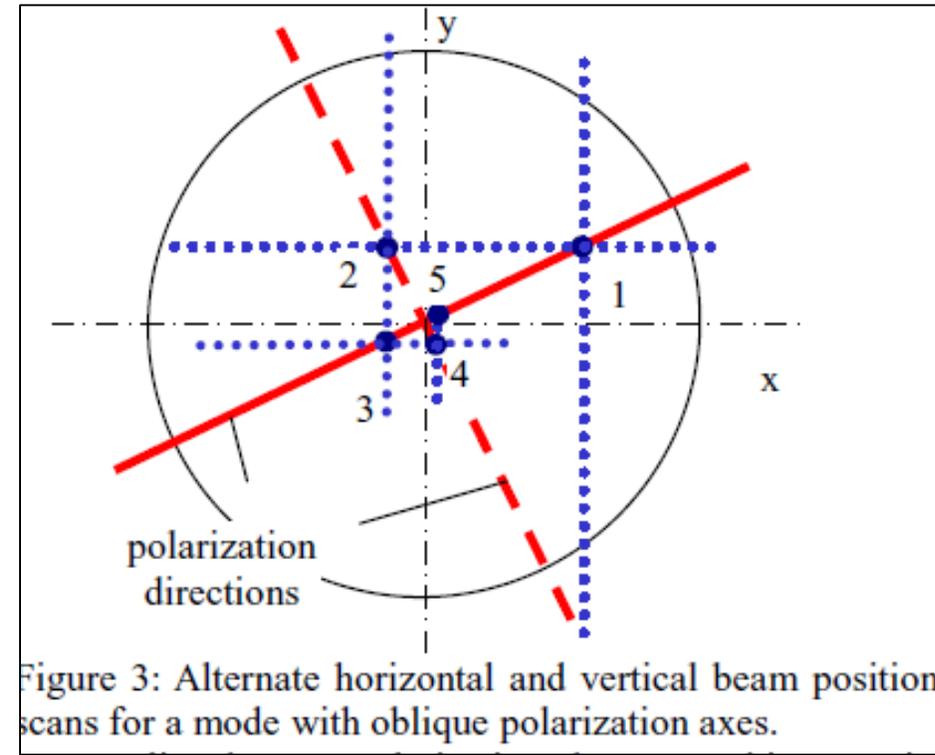


Figure 3: Alternate horizontal and vertical beam position scans for a mode with oblique polarization axes.

# Perform systematic studies for most significant HOM

- Measure the polarization angle by comparing the x vs. y sensitivities

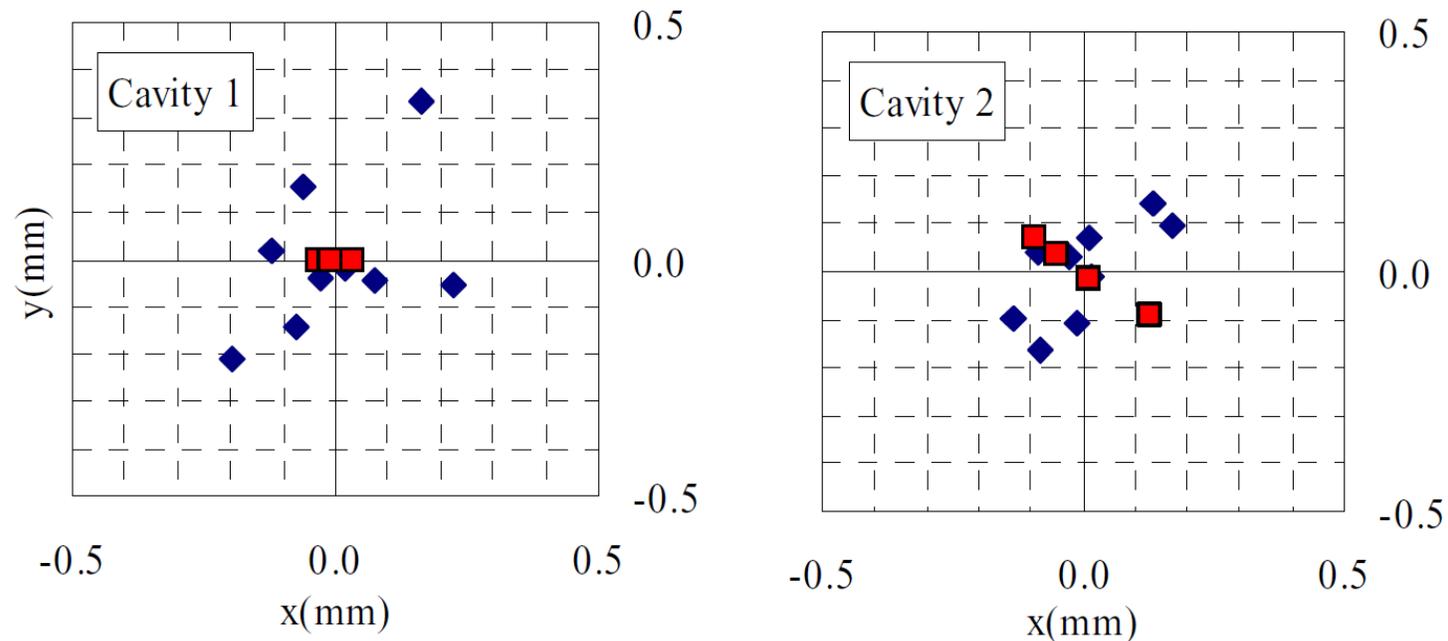
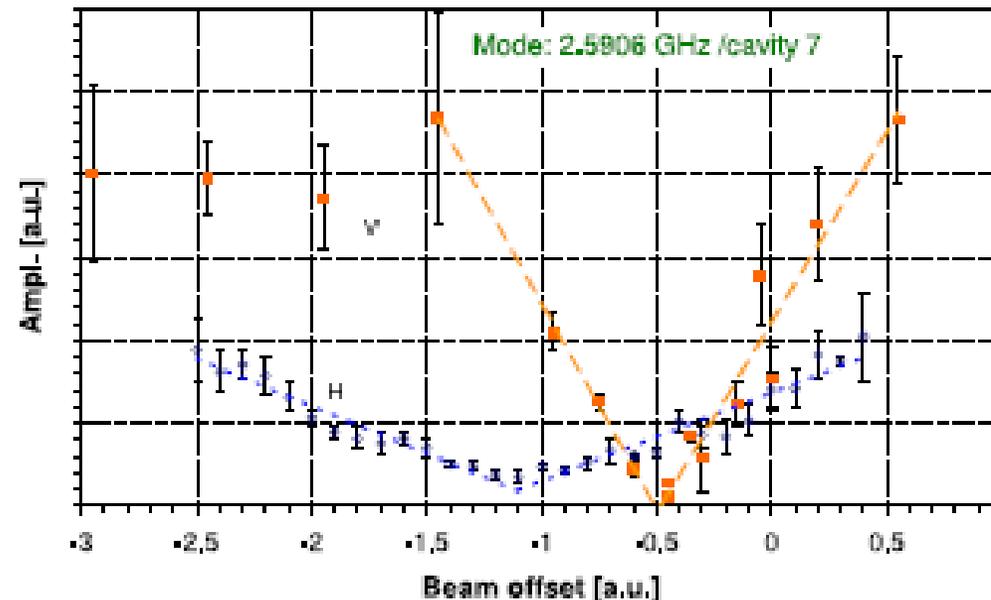


Figure 6: Relative positions of the 9 cell centers (blue diamonds) and of the 4 dipole mode centers (red squares).

# Measurement polarization angle

- Measure the polarization angle by comparing the x vs. y sensitivities

$$\tan \varphi = \frac{A(\delta x = 0, \delta y)}{A(\delta x, \delta y = 0)}$$



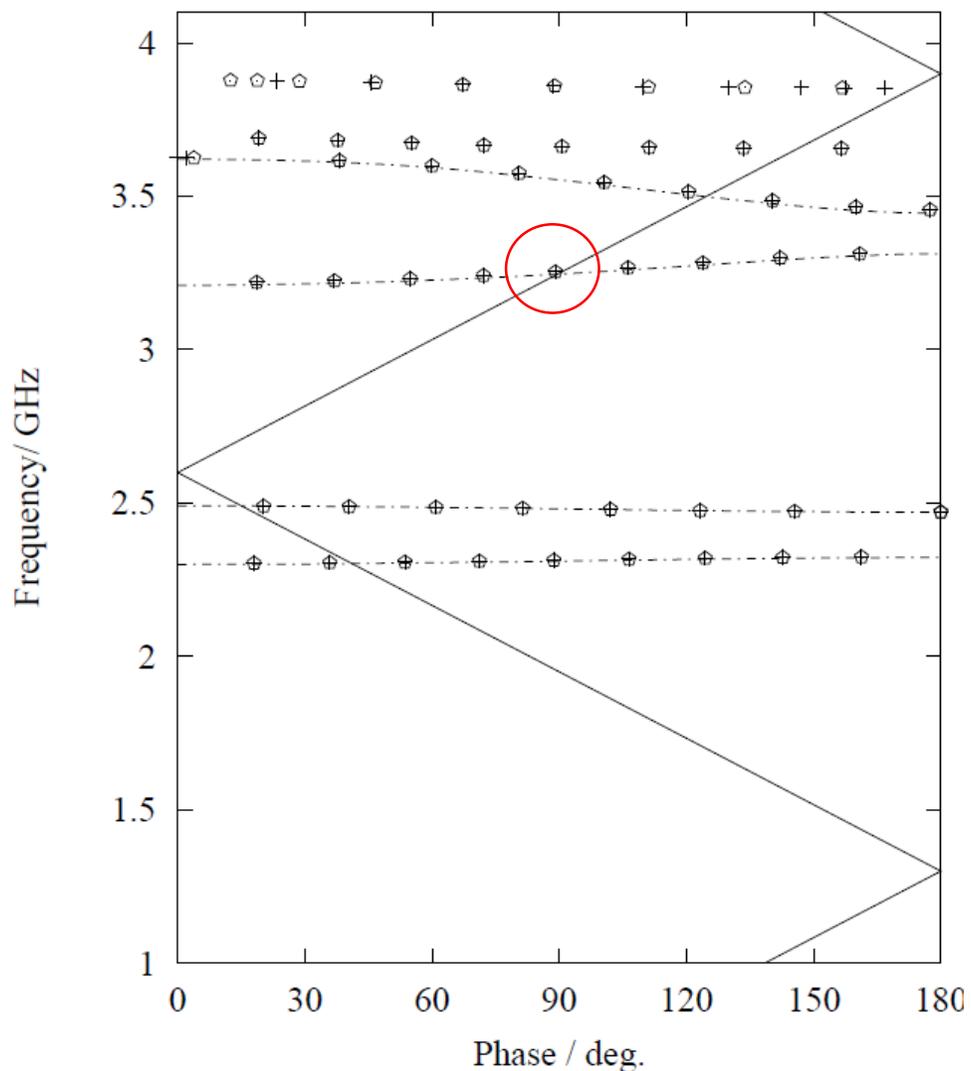
$77^\circ \pm 8^\circ$

Figure 5.28: Amplitude of signal from HOM couplers as a function of the horizontal and vertical beam offset.

# Questions to investigate:

- Are dipole modes preferentially 'H' and 'V', or at random angles ?
- Is there a correlation between dipole low / high frequency vs polarisation angle ?
- Once the mode center and polarization are determined, can one develop an online electronics to read the amplitudes  $A_1$  and  $A_2$ , and infer the single bunch transverse position  $\langle x \rangle$  and  $\langle y \rangle$  ?
- PIP-II cavities are not equipped with HOM damping couplers. Can we measure the HOM amplitudes from the RF-pick-up and to which accuracy ?

# Quadrupole modes in TESLA cavity



mode	$f$ / GHz	$k^{(2)}(r)/r^4 / V / (\text{pC m}^4)$	$G_1 / \Omega$	$(R/Q)^{(2)} / \Omega / \text{cm}^4$	$Q_0 / Q_{0FM}$	$\varphi / ^\circ$
Band 1						
MM- 1	2.3039	4946.0	455.6	0.0068	0.568	18.0
MM- 2	2.3052	48631.7	457.5	<b>0.0672</b>	0.570	35.9
MM- 3	2.3074	42191.1	460.5	<b>0.0582</b>	0.572	53.6
MM- 4	2.3101	1438.9	464.4	0.0020	0.576	71.2
MM- 5	2.3133	2776.0	468.9	0.0038	0.580	88.7
MM- 6	2.3166	207.5	473.7	0.0003	0.584	106.4
MM- 7	2.3197	420.9	478.6	0.0006	0.588	124.4
MM- 8	2.3224	30.8	483.0	0.0000	0.592	142.7
MM- 9	2.3242	29.1	486.1	0.0000	0.595	161.3
Band 2						
MM-10	2.4702	2.6	447.2	0.0000	0.485	180.0
MM-11	2.4706	3819.9	448.5	0.0049	0.486	180.0
MM-12	2.4727	1.2	451.5	0.0000	0.488	145.5
MM-13	2.4757	2932.4	457.0	0.0038	0.493	123.2
MM-14	2.4791	99.8	463.5	0.0001	0.499	102.1
MM-15	2.4825	5532.6	470.0	0.0071	0.505	81.3
MM-16	2.4856	979.7	476.0	0.0013	0.510	60.9
MM-17	2.4881	23777.3	480.7	0.0304	0.514	40.5
MM-18	2.4896	60355.0	483.7	<b>0.0772</b>	0.516	20.3
Band 3						
MM-19	3.2195	845.5	395.1	0.0008	0.252	18.6
MM-20	3.2242	8108.9	397.4	0.0080	0.253	37.0
MM-21	3.2316	6016.5	401.2	0.0059	0.254	54.8
MM-22	3.2414	201688.8	406.9	<b>0.1981</b>	0.256	72.1
MM-23	3.2532	453226.2	414.8	<b>0.4435</b>	0.259	89.1
MM-24	3.2670	286421.0	425.1	<b>0.2791</b>	0.263	106.2
MM-25	3.2825	35929.7	437.3	0.0348	0.269	123.8
MM-26	3.2985	4175.8	450.4	0.0040	0.274	142.1
MM-27	3.3120	4955.2	461.9	0.0048	0.279	160.9
MM-28	3.4561	32706.0	547.5	0.0301	0.303	177.5

Table 21: List of quadrupole modes in a 9-cell TDR-like TESLA cavity, 1st, 2nd and 3rd passbands, (magnetic boundaries). The parameters of the modes EE-1 to EE-28 (electric boundaries) are identical with the modes MM-1 to MM-28 of this table.



# Dipole Mode ( $m=2$ ) Excitation Amplitudes

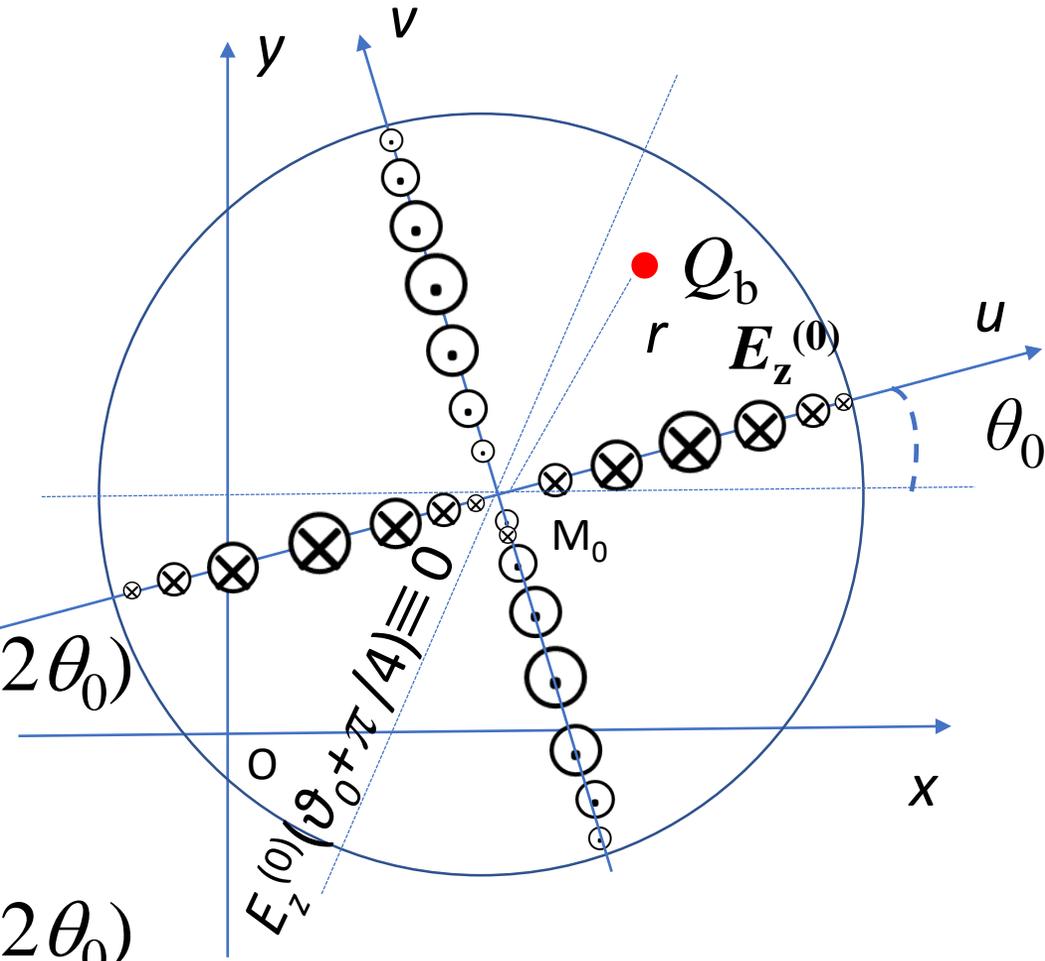
Assuming that both polarisations have the same center and beam coupling factor, for  $r \ll R$ :

$$A_1(Q_b) = C \langle r^2 \cos^2(\theta - \theta_0) \rangle = C \langle u^2 - v^2 \rangle$$

$$A_2(Q_b) = C \langle r^2 \sin^2(\theta - \theta_0) \rangle = C 2 \langle uv \rangle$$

$$A_1(Q_b) = C \text{Tr} \begin{pmatrix} \sigma_{xx} - (\langle x \rangle - x_0)^2 & & \\ & \ddots & \\ & & \sigma_3 \end{pmatrix} \cdot \mathbf{R}(2\theta_0)$$

$$A_2(Q_b) = C \text{Tr} \begin{pmatrix} \sigma_{xx} - (\langle x \rangle - x_0)^2 & & \\ & \ddots & \\ & & \sigma_1 \end{pmatrix} \cdot \mathbf{R}(2\theta_0)$$



# Quadrupole-modes Beam Size Monitor

In a perfect machine, i.e.:

- perfectly aligned cavities
- perfectly centered beam trajectory

through Ez-coupling, quadrupole mode signal is proportional to beam second moments, i.e. transverse beam matrix.

Therefore, one could consider 4D-emittance reconstruction if there is enough phase-advance that machine.

In a machine where these errors are larger than transverse beam sizes, the program might be unrealistic, because quadrupole signals will be dominated by beam offsets.

**In a machine with no too large errors, the large redundancy of HOM signals could be used to establish correlations between beam sizes and HOM signal magnitude.**

## Project Description

# Work Plan

The workplan of the project will include:

### HOM CARTOGRAPHY (with spectrum analyzer)

- Detailed characterization of the first dipole (1<sup>st</sup> to 3<sup>rd</sup>) and quadrupole (1<sup>st</sup> and 2<sup>nd</sup>) passbands of x-# SRF cavities (CM2).  
**Data exists at TD on dipole 1<sup>st</sup> and 2<sup>nd</sup> dipole passbands for 10 cavities, which ones are in CM2 ?**
- Verification of these characteristics (frequencies, damping time) from the beam excitation signal.
- Measurement of their electric center and polarization planes, by beam-based alignment techniques (single bunch).
- Determination the most precise higher order modes, namely with highest coupler impedance on the beam, and the lowest damping factor depending on beam resonance conditions.
- Study of a dedicated broad-band electronics for HOM signal acquisition

### HOM-BASED BEAM DIAGNOSTICS

- Utilization of the most adequate dipole modes for beam position measurement and beam steering, on average and possibly on a bunch-to-bunch basis. Characterization of the measurement precision and resolution.
- First studies of beam size measurement using the RF signal of the adequate quadrupole modes, on average and possibly on a bunch-to-bunch basis. Characterization of the measurement precision and resolution.
- Elaborated statistical and minimization techniques, such as SVD, will also be used to provide an overview of the beam trajectories and beam sizes along the FAST linac using the many and redundant RF signals coming from the 10 superconducting cavities.